SEPTEMBER 2020
VOL 60 NO. 3

GLOBAL GAS TURBINE NEWS

In this Issue...

ASME
Gas Turbine Segment
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ASME ADVANCED MANUFACTURING AND REPAIR FOR GAS TURBINES (AMRGT) Symposium

By Douglas Nagy, *Liburdi Turbine Services*

EVENT.ASME.ORG/AMRGT **FALL 2021**

Presented by ASME's Gas Turbine Segment (GTS) and International Gas Turbine Institute (IGTI) Division, the popular Advanced Manufacturing and Repair for Gas Turbine (AMRGT) two-day symposium will return for 2021.

This specialist event brings together engineers, designers, researchers, production engineers and business leaders from companies that design, manufacture, repair, and own gas turbines. Furthermore, AMRGT also appeals to individuals and companies that design and execute advanced manufacturing processes and equipment.

AMRGT explores the critical interdependence of production demand for lower costs, lighter environmental footprint, and faster more flexible fabrication and challenges those in our manufacturing process research and development community. Similarly, novel, and exciting processing techniques, often combining computer-aided design/manufacturing principles, results in new and more efficient ways to address component design and manufacture.

Coming out of the COVID-19 Pandemic, many companies have risen to the challenge to re-tool for pandemic support. Organizers expect an unprecedented pent-up demand for jet engine and gas turbine maintenance as the economy spools-up again. Upon return to the new-normal factory floors will place even stronger emphasis on de-bottlenecking, flexibility, efficiency, and worker-safety. The AMRGT is the key event for the professionals to network between developers and users and learn how to best take advantage of these new processes to support these arising needs in the turbomachinery industry.

AMRGT uses a presentation without publication format expressly to allow the rapid and timely transfer of information that is accessible to authors from all types of businesses. Keynote and educational seminars are included for all participants. Special Panel sessions encourage lively discussion of ground-breaking topics. Submit an abstract at *event.asme.org/AMRGT*.

Significance to the Community AMRGT Supports

Gas turbine and jet-engine industry has been wracked by a 'perfect storm' of both economic downturn and environmental awareness. Surveys have shown that although passenger flights may soon resume, the public is still hesitant to participate [1]. Furthermore, long periods of inactivity have taken a toll not only on the pocketbooks of operators, but also

For more information, contact *igtiprogram@asme.org*.

Pictured: AMRGT 2020

on the condition of the equipment. Deferred maintenance often leads to increased maintenance costs when executed.

Therefore, going forward, there will be strong demand for flexible repair options. Reopening a shuttered factory with an out-of-practice workforce will not be enough.

The AMRGT symposium encourages the interaction between the 'push' of technological advances out of academia and the technology 'pull' resulting from industry's needs. This is the universe where job-creation occurs, smart ideas meet technical capability to meet a commercial need. Evolving public policies emphasizing 'on-shore production' open new commercial opportunities every day.

Key Takeaways for Attendees

- Gain knowledge of the latest design strategies for additive-built parts and repair techniques from renowned experts.
- Contextualize how advanced manufacturing is changing business models and enhancing business transformation.
- Drive technology adoption through knowledge dissemination, workforce development, standards development, and conformity assessment solutions.
- Network with experts in advanced manufacturing for gas turbines.

1. Webinar: From crisis to complacency: mapping public opinion during the COVID-19 pandemic. Cliff van der Linden, McMaster University, June 29, 2020

Who Should Attend?

- Gas turbine manufacturing and design engineers
- Equipment and process designers for advanced manufacturing
- Gas turbines service and repair professionals
- Gas turbine asset owners involved with maintenance repair and overhaul (MRO)
- Secondary service providers for the gas turbine industry
- Engineers supporting MRO of gas turbine machinery
- Advanced coatings and welding processes engineering professionals
- Academics and students involved with design for advanced manufacturing

ASME TURBO EXPO 2020 VIRTUAL CONFERENCE

Virtual Event Dates
September 21-25, 2020

Register online at
event.asme.org/Turbo-Expo

UPCOMING AWARD OPPORTUNITIES

2021 ASME IGTI Aircraft Engine Technology and Industrial Gas Turbine Technology Awards

Nominations due to *igtiawards@asme.org* by October 15, 2020.

2021 Student Scholarships

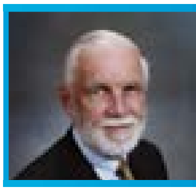
Application process is open December 1, 2020 – March 1, 2021.

For more information, visit *asme.org/asme-programs/students-and-faculty/scholarships*

Award Winners on Page 56

ASPECTS OF GAS TURBINE THERMAL EFFICIENCY

#43 - September 2020



By Lee S. Langston,
Professor Emeritus,
University of Connecticut

In the family of heat engines, the gas turbine is unique in that it is used to produce two different kinds of useful power. By converting combusted fuel heat into work, a gas turbine engine can produce external shaft power (e.g., to drive a connected electric generator) or jet power (e.g., as a jet engine, to produce thrust forces to propel an aircraft). This means that the gas turbine's thermodynamic figure of merit, thermal efficiency, is multifaceted, and calls for a nuanced examination.

The shaft power category here, covers the market for nonaviation gas turbines. The jet power category covers the market for aviation gas turbines, be they turbojets, turbofans. turboprop and helicopter engines, or auxiliary power units (APUs) (all of which, of course, have internal shaft power).

Thermal efficiency, η, is defined in simple words as *useful output* divided by *costly input*. The input is the rate at which energy is supplied to the gas turbine engine, calculated from a measured fuel flow rate and the fuel's heating value. The output power for a shaft power gas turbine can be measured under test [1] by a dynamometer or even a calibrated electrical generator. However, the power output of a jet engine in flight is difficult to measure directly. This would entail measuring the rate of production of kinetic energy of the gases passing through the engine, as well as engine thrust and flight velocity. Instead, jet engine OEMs measure engine thrust directly on a static test stand and appraise individual component efficiencies (compressor, turbine etc.) to infer performance.

Since η is such an important parameter in energy considerations, let us look at how it is treated from the standpoints of shaft power and jet power gas turbines. The ideal pattern cycle for all gas turbines, the Brayton cycle, will be called upon to provide help with some explanations.

Shaft Power

The world's first shaft power gas turbine was built and tested by Swiss firm Brown Boveri (BB) in 1939. It was a 4 MW output machine, originally installed in the city of Neuchâtel for electric power generation and is now displayed in a special museum in Birr, Switzerland.

According to our IGTI founder, R. Tom Sawyer, official testing of the world's first operational gas turbine began on July 7, 1939. In his 1945 textbook, *The Modern Gas Turbine* [1], Sawyer reviewed the test program carried out at the BB works in Baden. This very first shaft power gas turbine power plant had a thermal efficiency of 17.38%, based on the heating value of the fuel oil rate and the heat equivalent of the electrical output of the generator. Since the component efficiency of electrical generators is very high, the generally quoted thermal efficiency, for this very first shaft power gas turbine is η = 18%.

Since then, in the intervening 80 years, engineers have greatly increased gas turbine thermal efficiencies, with output as high as 500 MW. *Gas Turbine World* [2] cites specifications of simple cycle gas turbines manufactured by some two score OEMs. The highest measured thermal efficiency is 44.7% for General Electric's LMS100 model, an almost factor of three improvement from the Neuchâtel gas turbine.

Electric power plant operators have an "upside down" or reciprocal way of representing thermal efficiency values, going back to the early days of coal use for steam power (coal has a wide range of heating values). It is called "Heat Rate" (HR) and is defined as the amount of heat supplied (U.S. convention, in BTUs) to generate 1.0 kWh of electricity. For example, η = 44.7% quoted in the last paragraph, divided into energy conversion factor 3412 Btu/kWh, yields HR = 7628 Btu/kWh [2].

By the 1990s, gas turbine combustion and hot turbine technology had advanced to yield shaft power gas turbine exhaust gas temperatures high enough to be used to generate steam to power steam turbines. The resulting combined cycle power plant (Brayton and Rankine and abbreviated as CCGT) thus generates electric power from two prime movers using one unit of fuel (usually natural gas).

From conservation of energy and the definition of thermodynamic thermal efficiency, η, the combined cycle thermal efficiency, η_{CC}, can be derived fairly simply as,

$$\eta_{CC} = \eta_B + \eta_R - \eta_B \eta_R \quad (1)$$

where η_B and η_R are thermal efficiencies of the Brayton and Rankine cycles, respectively. Taking η_B = 40% (a good value for modern gas turbines) and η_R = 30% (a reasonable value at typical CCGT conditions), the sum minus the product in Equ. (1) yields η_{CC} = 58%, a value of combined cycle efficiency greater than either of the individual efficiencies.

Currently, CCGTs are achieving plant efficiencies of as high as 64% [2], with outputs in the 900 MW range. These then, are the most efficient heat engines yet perfected by mankind.

Jet Power

The use of an ideal thermodynamic analysis for an ideal turbojet in flight can provide a straightforward way to shed light on aspects of jet power thermal efficiency, brought about by flight Mach numbers.

Figure 1. Ideal Turbojet

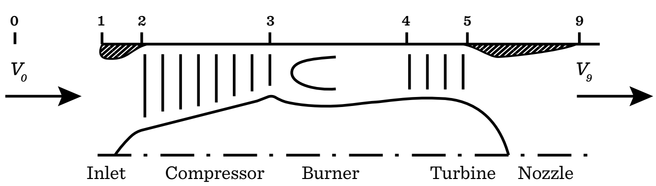


Figure 1, taken from Oates [3] shows a simplified cross section of an idealized fixed turbojet in an approaching ideal gas flow at flight velocity V_0 and Mach number M_0. (The numbering of engine stations conforms to standard practice and the fuel mass addition is neglected.)

Figure 2 is a Brayton cycle temperature-entropy (T-s) plot, with labeling to identify each part of the cycle. In particular, isentropic compression consists of a ram compression part, 0—2, and the compressor part, 2—3. The latter yields the compressor pressure ratio (total to total), PR. The isentropic expansion is made up of flow through the turbine, 4—5, with the remainder of the expansion, 5—9, from the turbine exit to flight atmospheric conditions.

Thermal efficiency for the ideal cycle shown in the T-s diagram is also the ratio of the area enclosed by the cycle to the area under the heat addition process, 3—4. Thus, one can see the area contribution to thermal efficiency of the flight conditions, 0—2 and 5—9.

Using Fig. 2 and ideal cycle analysis, it can be shown [3] that the ideal turbojet thermal efficiency, η, is given by

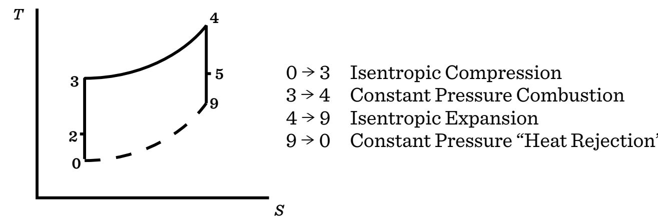
$$\eta = 1 - \frac{1}{\left(1 + (\gamma - 1)/2(M_o^2)\right)(PR)^{(\gamma-1)/\gamma}} \qquad (2)$$

where γ is the ratio of ideal gas specific heats.

Thus, from Equ. [2] we see that the ideal jet power turbojet thermal efficiency increases with compressor pressure ratio, PR, and as the flight Mach number M_0 (squared) is increased.

If we assume PR = 40 (typical of many commercial aviation engines) and an airline cruise Mach number of M_0 = 0.8, Equ. (2) yields a value of η = 69%. For the no-flight case of M_0 = 0, Equ. (2) yields η = 65%, amounting to a 6% decrease from M_0 = 0.8. This then gives an illustration of the important

Figure 2. Temperature Entropy Diagram



difference associated with ram compression that can arise between shaft power and jet power thermal efficiencies.

Last Words

The two ideal values of η calculated in the last section, 69% and 65%, are greater than would be expected from a real turbojet, since component losses and real gas effects were not considered. Each jet engine OEM has their own procedures for accounting for the losses.

However, even when these loss effects are taken into account, the values of flight jet engine thermal efficiencies can still be greater than shaft power gas turbines. For instance, Epstein and O'Flarity [4] report values of flight jet power thermal efficiencies as high as 55% for large turbofan engines at cruise conditions, significantly greater than the current measured peak value of 45% for shaft power gas turbines.

In summary, the ideal thermodynamic analysis in the last section showed that the contributions of flight conditions increased ideal turbojet thermal efficiency as the Mach number squared.

An extreme example of this flight enhancement is the performance of the supersonic SR-71 Blackbird reconnaissance aircraft, which was powered by two Pratt & Whitney J58 turbojet/ramjet engines [5]. Actual engine thermal efficiencies aren't available, but at its design cruise speed of M_0 = 3.2 and an altitude of 100,000 feet, only 18% of its thrust was provided by its turbojets, while the pressure recovery in the engine inlets contributed 54%, with the remainder of thrust coming from the engine ejector nozzles. Real flight conditions do have an effect on enhancing the performance of jet power gas turbines.

1. *Sawyer, R. Tom, 1947, The Modern Gas Turbine.*
2. "Gas Turbine World 2018 Performance Specs", 2018, *Gas Turbine World*, Vol. 48, No. 3, July-August, p. 11.
3. Oates, Gordon C. 1984, *Aerothermodynamics of Gas Turbine and Rocket Propulsion*, AIAA Education Series, pp. 122-124.
4. Epstein, Alan H. and O'Flarity, Steven M., 2019 "Considerations for Reducing Aviation's CO2 with Aircraft Electric Propulsion", AIAA *Journal of Propulsion and Power*, Vol. 35, No. 3, May.
5. Langston, Lee S., 2013, "Powering Out of Trouble", *Mechanical Engineering Magazine*, December, pp. 36-41.

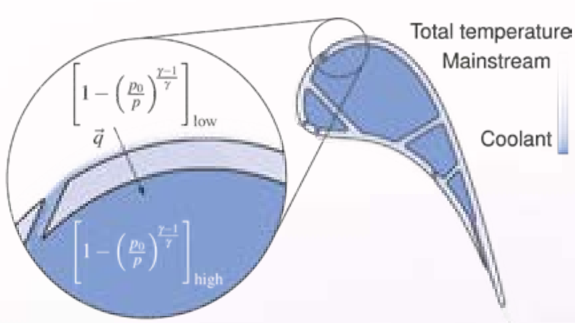
THE EFFECT OF HEAT TRANSFER on Turbine Performance

By Lachlan J. Jardine and Robert J. Miller,
Whittle Laboratory, University of Cambridge

What's the Problem?

For over 50 years, high-pressure gas turbine blades have been cooled using air bled from the compressor. This cooling results in very high rates of heat transfer, both within the fluid and within the blade, shown in figure 1. The heat transfer often occurs across large temperature differences and is thus highly irreversible. It is therefore surprising that little is understood about the effect of this heat transfer on turbine performance.

Figure 1. Heat Transfer Across a Difference in Joule Cycle Efficiency (Conjugate CFD Solution)



The effect of cooling on performance has been investigated in several important studies (Horlock [1], Denton [2], Young & Wilcock [3]). These studies have all adopted an entropy-centric (exergy) approach to performance analysis, in which the entropy created within the turbine is used to measure the loss of performance. In a cooled turbine, the entropy created due to heat transfer between the hot mainstream flow and the cooler coolant flow is extremely large (i.e. sufficient to reduce turbine efficiency by around 4-6%). In practice, this drop in efficiency is not observed. In fact, industrial designers are so confident that heat transfer does not have a large effect on efficiency that they measure the efficiency of cooled turbines using isothermal turbine test facilities (i.e. with the mainstream and coolant set to the same temperature). The direct contradiction between an entropy-centric approach to performance analysis and the experience of designers can be explained for simple cases but, until now, no solution existed for more complex, engine representative cases.

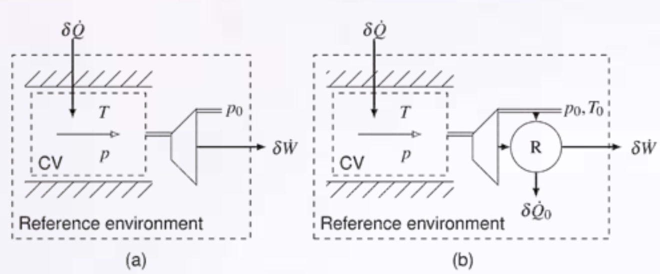
The New Approach

The new approach was developed by Miller [4] and is known as mechanical work potential, or euergy[1]. This method is based on the simple idea that the ideal work, to which a turbine designer aspires, is the work that can be extracted by a reversible adiabatic turbine (i.e. a reversible adiabatic expansion to the fixed exhaust pressure). A key consequence of this method is that the value of all heat, in terms of the work that can be extracted from it, is set by the Joule (Brayton) cycle efficiency. This result can be easily shown using the simple example in figure 2. A small heat addition, $d\dot{Q}$, is transferred to the flow of a perfect gas. The ideal method of work extraction is defined as the work that can be extracted by a reversible adiabatic turbine exhausting to an environmental pressure, p_0. The increase in the rate of work is:

$$d\dot{W} = \left(1-\left(\frac{p_0}{p}\right)^{\frac{\gamma-1}{\gamma}}\right)d\dot{Q}$$

More generally, if a euergy approach is taken then the value placed on all heat addition, locally within the flow, is set by the Joule (Brayton) cycle efficiency.

Figure 2. Relative Value of Heat and Work: (a) Euergy Method, (b) Exergy Method



The Difference Between the Traditional and New Approaches

The fundamental difference between the two approaches is the ideal work to which a turbine designer aspires. The exergy (entropy) method is based on the idea that the ideal work is the work that can be extracted by a universal reversible machine which can bring the flow to the pressure and temperature of the environment. To achieve this, a reversible adiabatic turbine is required to bring the flow to the environmental pressure, p_0, and a reversible heat engine is required to bring the flow to the environmental temperature, T_0. In contrast, the euergy method is based on the idea that the ideal work is the work that can be extracted by a reversible adiabatic turbine which can bring the flow to the environmental pressure only. The exhaust of the turbine is at a temperature that differs from the temperature of the environment. The extra work that could be extracted from it is considered lost in the exhaust.

The key consequence of this choice of method is the value placed on heat. For the euergy method, the value placed on all heat is set by the Joule cycle efficiency. For the exergy method, the value placed on all heat is set by the Carnot cycle efficiency.

$$d\dot{W} = \left(1 - \frac{T_0}{T}\right) d\dot{Q}$$

The euergy method represents the true aspiration of the turbomachinery designer (to design reversible adiabatic turbomachines).

The Recuperation Effect

The new approach shows that heat transfer within the blade row can act to reduce the loss coefficient of a blade row (i.e. raise stage efficiency). This may at first seem strange. The physical mechanism responsible for this effect can be understood by considering a small heat flux, $d\dot{Q}$, passed between two streams of a perfect gas. If the pressure of the hot stream is lower than the pressure of the cold stream, then heat is transferred from a low to a high Joule cycle efficiency. This increases the rate of work which can be extracted from the flow by

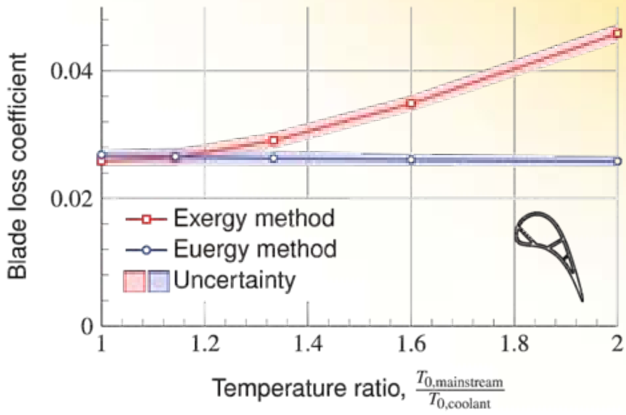
$$d\dot{W} = \left(\left(\frac{p_0}{p_{low}}\right)^{\frac{\gamma-1}{\gamma}} - \left(\frac{p_0}{p_{high}}\right)^{\frac{\gamma-1}{\gamma}} \right) d\dot{Q}$$

The increase in work that can be extracted from the flow comes from a recovery of energy from the hot turbine exhaust. The effect can be thought of as a form of recuperation, a recovery of energy which would otherwise have been wasted in the turbine exhaust.

Impact of Heat Transfer

Jardine and & Miller [5] showed the impact of heat transfer on turbine rotor loss, shown in figure 3. As the ratio of mainstream-to-coolant temperature ratio is increased, the exergy method shows the blade loss rises by 60%. The euergy method however shows that the blade loss falls by 3.6%. The fall is the result of the recuperation effect. The euergy method exhibits the experience of industrial designers; that heat transfer does not have a large effect on efficiency.

Figure 3. Comparison of Exergy and Euergy Loss Coefficients



Implications

The recuperation effect offers a new way of raising turbine efficiency. Jardine and Miller [5] show that, by moving from externally to internally cooled blades, a potential reduction of blade loss of ~7% can be achieved. Now that a systematic method of analysing cooled component performance has been developed, we have the exciting opportunity to undertake a truly aerothermal optimisation of the new, and highly complex, cooling geometries enabled by additive manufacture.

The euergy method also offers a new way to analyse air-breathing engines, i.e. engines which exhaust to a fixed environment pressure. For such devices the euergy method should be used to guide design, while the more traditional exergy method should be used as a measure of the upper efficiency limit of the engine.

[1] Euergy from the Greek eu and ergon meaning good or useful work. The 'eu' is pronounced as in eulogy, in the classical Greek pronunciation.

1. Horlock, J. H., 2001. "The basic thermodynamics of turbine cooling". ASME J. Turbomach., 123(3), pp. 583–592.
2. Denton, J. D., 1993. "Loss mechanisms in turbomachines". ASME J. Turbomach., 115(4), p. 621.
3. Young, J. B., and Wilcock, R. C., 2002. "Modeling the air-cooled gas turbine: part 2—coolant flows and losses". ASME J. Turbomach., 124(2), p. 214.
4. Miller, R. J., 2013. "Mechanical work potential". In Proceedings of ASME Turbo Expo 2013: Power for Land, Sea and Air. Paper No. GT2013-95488.
5. Jardine, L. J., and Miller, R. J., 2019. "The effect of heat transfer on turbine performance". In Proceedings of ASME Turbo Expo 2019: Power for Land, Sea and Air. Paper No GT2019-91556.

AWARD WINNERS

Congratulations to all award recipients and thank you to all ASME IGTI committee award representatives whose work assists the awards and honors chair and the awards committee in the recognition of important gas turbine technological achievements. Thank you to John Blanton for serving as the IGTI Honors and Awards Committee Chair, John Gülen as Industrial Gas Turbine Technology Award Committee Chair, and Andrew Nix as the Aircraft Engine Technology Award Committee Chair.

2020 ASME R. Tom Sawyer Award

Sunao Aoki, *Mitsubishi Heavy Industries*

2018 ASME Gas Turbine Award

Bogdan Cernat, *von Karman Institute for Fluid Dynamics*

Marek Pátý, *Department of Technical Mathematics*

Dr. Cis De Maesschalck, *Rolls Royce*

Dr. Sergio Lavagnoli, *von Karman Institute for Fluid Dynamics*

2018 John P. Davis Award

Dr. Sung Choi, *Naval Air Systems Command*

David Shifler, *Office of Naval Research*

2020 ASME Dedicated Service Award

Dr. Michael Klassen, *Combustion Science & Engineering, Inc.*

Dr. Atul Kohli, *Pratt & Whitney*

2020 Aircraft Engine Technology Award

Dr. Wing Ng, *Virginia Tech*

2020 Industrial Gas Turbine Technology Award

Dr. Thomas Sattelmayer, *Technical University of Munich*

2020 Dilip R. Ballal Early Career Award

Dr. Reid Berdanier, *Penn State University*

Congratulations to the Student and Young Engineer Winners:

Young Engineer Turbo Expo Participant Award Winners (YETEP)

Mahmood Alqefl

Maria Alessadandra Ancona

James Braun

Elise Delhez

Scott Egbert

Saarthak Gupta

Xiao He

Shreyas Hedge

Daniel Inman

Hardik Jani

Andressa Johnson

Hussain Kaizar

Zhihui Li

Marco Manfredi

Luca Mantelli

Izzet Sahin

Hari Shrestha

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Xing Yang

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Tânia Sofia Cação Ferreira

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Avinash Ambadas Renuke

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Matthew Aaron Meier

Louis Edward Christensen

Alessandro Romei

Brian Frederick Knisely

Kedar Prasad Nawathe

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